THE ORIGIN OF THE INCLUSIONS IN DIKES

SIDNEY POWERS
Geological Museum, Cambridge, Massachusetts

PART II

(*C*) *Many inclusions have risen.*—

Shelburne Point, Vermont: On Shelburne Point and on Nash's Point, near-by, a few miles south of Burlington, Vermont, are several inclusion-bearing dikes of great interest. They have been described by Hitchcock[1] and by Kemp and Marsters.[2] On both sides of Shelburne Point are outcrops of a 20-foot bostonite dike filled with angular inclusions of Middle Ordovician shale and red Cambrian quartzite. These inclusions have sharp edges and do not appear to have been noticeably altered by the bostonite. On Nash's Point is another bostonite dike, about 12 feet wide and vertical, with chilled margins 2 feet and 1 foot wide on the respective sides of the dike, and a mass of fragments in the middle. A part of the fragments are quite angular and a part decidedly rounded. They vary in size from a fraction of an inch to 4 or 5 inches in length, but Kemp and Marsters found one piece of norite 18 feet in diameter. They consist of garnetiferous hornblende schist, pre-Cambrian norite, quartz, grey sandstone, red Cambrian sandstone, Trenton shale, and black limestone, cemented by a bostonite groundmass. Kemp and Marsters add: "Under the microscope, sections of norite show plagioclase and garnet, all exhibiting the results of dynamic action. Sections of the red quartzite have the usual fragmental character, with the evidences of strain less developed." The presence of the norite and schist inclusions show that the dikes have come through an indefinite amount of the pre-Cambrian as well as through Cambrian sandstone and Ordovician limestone into

[1] "On Certain Conglomerated and Brecciated Trachytic Dikes in Vermont," *Proc. Amer. Ass. Adv. Sci.*, XIV (1860), 156.

[2] "Trap Dikes of the Lake Champlain Region," *U.S. Geol. Surv., Bull. 107*.

their present position in Middle Ordovician shales. On the end of Nash's Point a 10-foot sill of bostonite is filled with unaltered shale inclusions from the immediate walls.

Kemp and Marsters have the following suggestions to offer concerning the manner in which the dikes acquired the inclusions:

> Two explanations may be offered for this rock. One, that it has been intruded in a line of previous faulting and attrition, which has broken up the walls and left loose material to be gathered up by the intrusive magma. This explanation has the greater weight with the writers. The other is that it represents only the upper portion of a dike and thus contains the float material which the advance of an intrusive body, that forced its own passage, would naturally gather from its walls. The lack of such inclusions in the neighboring dikes may be due to the fact that their tops have been eroded.

The difficulty with the first explanation is that there is no evidence of any faulting with brecciation at the particular places where the dikes came up. Moreover, how did the sill which follows a sharp fold in the shale obtain its inclusions by this hypothesis? It would appear extraordinary for faulting to occur in both a vertical and nearly horizontal position (the shales having a low dip) and to have brecciation occur only in these particular cases. The second explanation is partly in accord with the theory about to be proposed, but there is no reason why these should be the top of the dikes, or why the dikes for some distance vertically should not be equally filled with inclusions.

The origin of the inclusions appears to the writer to have been the shattering of the walls of the dike by the intrusive magma as it ascended through the pre-Cambrian, Cambrian, and Ordovician. Little corrosion could take place in fragments caught in such a magma and shot upward to their present position where they would be quickly chilled because of the inadequate supply of heat and lack of time. The invaded rocks would be comparatively cold when ripped off, and would therefore have a chilling effect upon the surrounding dike-magma in a 20-foot dike. Kemp and Marsters found the bostonite to be porphyritic, with a fine groundmass showing flow-structure around the inclusions. The rounded character of some of the inclusions is probably due to mechanical causes, principally the friction of the blocks against the walls of the dike

and against each other in ascent. The thickness of the sedimentary series in the region is about 12,000 feet from the top of the pre-Cambrian to the horizon of the outcrop of the dike. Hence, the pre-Cambrian norite inclusions must have risen over two miles and their edges would be necessarily rounded.

The abundance of the inclusions in two dikes and a sill, while other near-by dikes of the same composition and age do not show any inclusions at the present exposure, is not sufficient evidence to prove that all of the dikes do not contain inclusions in place. The shattering of the walls of some of the dikes may have been a purely accidental phenomenon, due to the way in which the fissures formed through which the magma came. If the passage were through a vertical fissure with straight unbroken walls, no inclusions would be expected.

Mancos, Colorado: Professor Kirtley F. Mather, of Fayetteville, Arkansas, has kindly contributed the following account of the inclusions in dikes near Mancos, Colorado:

In the San Juan region of southwestern Colorado, about 8 miles southwest from the town of Mancos, there is a small area of igneous rock which is locally known as "the Blow-out." The Mancos River at this point is flowing in a steep-sided youthful valley cut through the Mesaverde formation, which caps the neighboring plateaus, and far into the Mancos shale. "The Blow-out" is situated high up on the eastern slope of the valley in the midst of the maturely dissected shales. It consists of a conical mound about a quarter of a mile in diameter and two or three hundred feet in height, composed of mediosilicic extrusive volcanic material, flows, tuffs, and breccias. Cutting the volcanic cone and the surrounding country rock there are several subsilicic dikes which vary in width from an inch to 4 or 5 feet. The more prominent of these dikes can be traced for many hundred yards outward beyond the boundary of the central cone. Both the extrusive and intrusive rocks contain an abundance of inclusions of several different types of rock materials.

The extrusive volcanic rock varies considerably in its composition in different parts of "the Blow-out," but typically it is an andesite consisting of plagioclase feldspar, about $Ab_{55}An_{45}$, accompanied by biotite, magnetite, and augite, imbedded in a glassy matrix. The dike rock likewise is quite variable in composition, but it consists essentially of phenocrysts of biotite, augite, olivine, and plagioclase, imbedded in a groundmass of glass, pyroxene, felty plagioclase, magnetite, and biotite. The percentage relations of the minerals in the phenocrysts is notably different in different parts of the same dike, but usually the rock is rich in biotite and poor in plagioclase. The latter is little, if any, more calcic than that in the extrusive rocks.

Inclusions in the dike-rocks are extremely numerous and vary in size from tiny fragments up to masses nearly 3 feet in length. They consist of rounded, subangular, or occasionally angular, fragments of shale, sandstone, granite, metamorphosed limestone, and quartzite conglomerate. The inclusions of sedimentary rock are relatively abundant in approximately the same proportions as those in which the shales, sandstones, limestones, and conglomerates occur in the underlying sedimentaries—the Mancos shale, the Dakota sandstone with its basal conglomerate, the McElmo and LaPlata formations, etc. In the thicker dikes, shale inclusions are more numerous near the contact walls than toward the middle of the dike. The inclusions of sedimentary rocks are evidently fragments from the walls of the conduits through which the lava passed upward and from which they were torn by some process analogous to stoping. They all show the effects of their immersion in the molten mass with which they were surrounded.

The origin of the granitic inclusions is less apparent. No granites are known to outcrop within the drainage basin of the Mancos River, which includes much of the LaPlata Mountains northeast from Mancos. It is believed, however, that their origin must be similar to that of the other inclusions in the same dikes, and hence it is inferred that beneath the sedimentary rocks which outcrop in this region there must be a body of granite which was likewise cut by the dikes and from which fragments were torn by the ascending lavas in the same manner as those from the overlying strata. Such a granite mass might be either an intrusion into the sedimentaries, preceding the vulcanism, the effects of which are now displayed at the surface, or it might be a hill of pre-Cambrian or Paleozoic rock around and above which the Mesozoic sediments were laid down. These inclusions of igneous rock display a remarkable selective assimilation by the dike-magmas of certain of the minerals of the granite. This will be discussed in a paper now in preparation.

Aschaffenburg, Germany: In the Spessart region near Aschaffenburg there are a number of lamprophyre dikes, some of which contain inclusions of granite or of minerals derived from an augen gneiss. In the Schweinheimer kersantite dike, Thürach[1] has found inclusions 40 cm. in diameter, of a granite which contains orthoclase augen 5 cm. in length. Goller[2] has described quartz and orthoclase inclusions from similar dikes. The quartz fragments are rounded, and have a maximum length of 10 mm. The orthoclase fragments are less abundant and have a maximum length of 6 cm. These inclusions are scattered through the dikes. They

[1] "Über die Gliederung des Urgebirges im Spessart," *Geogn. Jahreshefte*, V (1893), 101.

[2] "Die Lamprophyrgänge des südlichen Vorspessart," *Neues Jahrb. f. Min.*, Beilageband VI (1889), 521 ff.

have come from the same underlying gneiss as the granite fragment. The selective action of the dike-magma in including fragments of only quartz and feldspar from the underlying gneiss is comparable to the case at Mancos. This fragmentation is favorable to the contention of Day, Sosman, and Hostetter[1] that the shattering of a siliceous rock is due principally to the expansive force of quartz at the inversion point of 575°C.

Somerville, Massachusetts: In Somerville and Medford, Massachusetts, are a number of exposures of diabase dikes, among which the Medford dike and the dikes of the Mystic River quarry carry inclusions. These dikes have variable mineralogical compositions. The Medford dike cuts Cambridge slate (probably of Permian age) and the older igneous complex of the Middlesex Falls. It varies in width up to 270 feet, and is probably over 4 miles in length. The Mystic River dikes cut the Cambridge slates, and are less than 10 feet in width. The inclusions in these dikes are chiefly composed of aggregates of single minerals, with vein quartz predominating. They are usually less than 6 inches in diameter and have well-rounded surfaces. Some of the quartz inclusions are fully 2 feet in diameter. A list of the inclusions found in the Medford dike includes[2]: quartz-diorite pegmatite, granite, graphic granite, diorite, quartzite, quartz schist, slate, quartz, feldspar, hornblende, and apatite. The inclusions in the Mystic River quarries are: altered biotite granite surrounded by a secondary rim of finer granite which has recrystallized with more femic constituents, diorite, pegmatite, quartzite, quartz, andesine feldspar (Ab_4An_3), hornblende, biotite, magnetite, apatite, zircon, and graphite.

The quartz inclusions are of especial interest and have been described by T. A. Jaggar, Jr.[3] These fragments have an irregular, clastic form. Sometimes the edges are rounded and sometimes very angular, with frequent embayments from magmatic corrosion.

[1] "The Determination of Mineral and Rock Densities at High Temperatures," *Amer. Jour. Sci.* (4), XXXVII (1914), 1–39.

[2] In making out these lists the writer has looked through the collections made by Professors Jaggar, Woodworth, and Palache, and is indebted to them for permission to publish the results.

[3] "An Occurrence of Acid Pegmatite in Diabase," *Amer. Geol.*, XXI (1898), 203–13.

A narrow-necked embayment, 3 inches in depth in the end of an inclusion 1 foot in length and 3 inches in width, has been noted by Jaggar. The quartz inclusions all appear to be surrounded by a wreath of augite prisms about 1 mm. wide, characteristic of quartz inclusions in basalt. This endomorphic reaction rim was found by Jaggar to consist of four zones between the diabase and the quartz: (1) diabase feldspar, (2) augite crystals, (3) potash feldspars, (4) micropegmatite.

The inclusions in these dikes appear to have been principally derived from rocks underlying the Cambridge slate. Very coarse diorite pegmatites, specimens of which have been found at Kidder Avenue in the Medford dike, and quartz veins seem to have furnished most of the material for the inclusions, the fragments of rocks being quite scarce, as would be expected in normal dikes shattering a few blocks off their walls during their ascent. The diorite pegmatite is not exposed in the vicinity of the dikes unless it is the same as that described by Jaggar near Arlington Heights.

These inclusions may have floated up in the dike-magma or they may have been forced up by it. Day *et al.* (*op. cit.*) have shown that the density of diabase glass is 2.763 and therefore heavier than the mineral xenocrysts. Whether the latter were formed by the differential expansion of the various minerals, a theory whose importance is emphasized by Goldschmidt,[1] or whether they were formed by purely mechanical action, is not clear. Numerous small xenocrysts of quartz and feldspar, from the vein quartz and diorite pegmatite, are found throughout the diabase, at least part of which have been broken off the corners of the inclusions.

Quartzose inclusions appear to be corroded frequently in igneous masses. A number of cases of reaction rims around quartz inclusions in extrusive rocks will be found described by Lacroix.[2] In the Globe district, Arizona, intrusive diabase contains numerous inclusions of vein quartz which are conspicuously corroded and embayed and surrounded by reaction rims of amphibole.[3] The

[1] *Die Kontaktmetamorphose im Kristianiagebiet* (1911), pp. 107–9.

[2] "Les enclaves des roches volcanique," *Annales de l'Académie de Mâcon*, X (1893).

[3] *U.S. Geol. Surv., Geol. Atlas*, Globe Folio (No. 111), 1904. Other diabase intrusions are described which contain many inclusions which have sunk.

Firth of Forth, Scotland, quartz diabases owe their free silica to solution of acid country rocks in normal diabase and contain corroded quartzose inclusions.[1]

Ogunquit, Maine: About 2 miles south of Ogunquit, Maine, several inclusion-bearing sills are exposed on the seashore halfway between Perkins Cove and Bald Head. The rocks of the region consist of thick-bedded slates, tilted into a vertical position with a uniform northeast strike, cut several miles inland by biotite granite. The slate is intruded by vertical trap sills of two or three generations, the older ones being porphyritic. The sills are mostly 5 feet or less in width, but one is over 50 feet wide. Most of the inclusion-bearing sills are of this older porphyritic type, which is seen under the microscope to be an augite-biotite kersantite. The sills occasionally cut across the bedding of the slates. They are younger than the frequent quartz veins which cut the slate.

In many of the sills in the vicinity there are a few inclusions. The latter are often 6 to 8 inches in length, with their longer axes parallel to the sides of the sill. In one sill, 2 feet, 10 inches wide, are two rounded inclusions of coarse graphic granite about 16 and 12 inches in diameter respectively, an angular block of granite 16 inches long and about 3 inches wide, with smaller subangular fragments of quartz and granite. There is a fused contact around all these inclusions. A 7-foot sill contains in one place many small subangular and rounded fragments of quartz, granite, syenite, and slate.

The principal inclusion-bearing sill is exposed for about 400 feet, showing a variation in width from 3 to 5 feet. It runs parallel to the stratification and has resisted erosion by the sea, while the slates on one side have been eroded away. The sill is cut by two younger dikes.

The character of the inclusions varies greatly. They are composed, in order of relative abundance, of a moderately coarse-grained light-colored syenite with green hornblende as the dark constituent; a coarse-grained granite resembling the syenite but containing free quartz; fine-grained pink and white aplitic granites which are probably biotite granites; fine-grained syenite seen in

[1] E. Stecher, *Tschermak's Mitt.*, IX (1888), 193.

thin section to consist principally of microperthite and oligoclase feldspars, with chlorite and other alteration products and a few grains of quartz; slate similar to the slate adjoining the sill; and vein quartz evidently derived from the veins which cut the slate. The size of the inclusions ranges from a few inches to 4 feet in length, in various parts of the sill. Thus, the inclusions in the part shown in the left-hand section of Fig. 1, where the sides of the sill are chilled, have an average size of 8 inches long by 4 inches wide. Nearer the sea, the margins of the sill do not show chilling, as

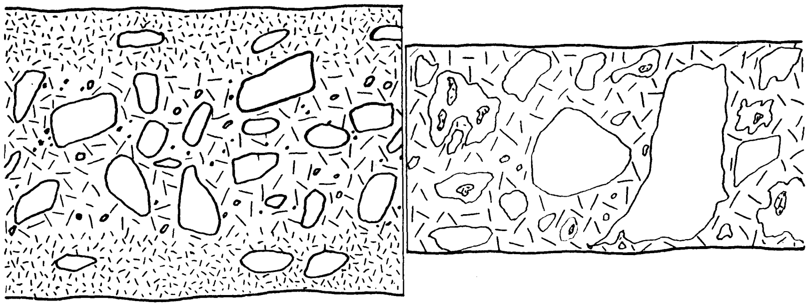

FIG. 1.—Two portions of the inclusion-bearing sill at Ogunquit, Maine. In the left-hand section the walls of the sill are chilled and the fragments show fused contacts but not resorption. In the right-hand section—about 100 feet away—the inclusions are being resorbed and their edges are indistinct. The width of the sill in the right-hand section is $3\frac{1}{4}$ feet.

shown in the right-hand section of Fig. 1, and here the average length of the fragments is about 1 foot. In the first area the inclusions have subangular to rounded outlines and tightly sealed contacts. In thin section the quartz from the aplitic granite can be seen to have migrated a sixteenth of an inch into the labradorite-augite-biotite matrix of the sill, but the feldspars from the coarse syenite have not migrated. In the second area, the inclusions all have corroded margins and the keratophyre may be seen to have worked its way into the coarsely crystallized syenite and granite. Blocks of the pink aplitic granite 3 and 4 feet long respectively and about $1\frac{1}{2}$ feet wide, with their longer axes orientated in some cases perpendicular to, and in other cases parallel to, the walls of the sill, where the latter is $3\frac{1}{4}$ feet wide, show that they have been

subjected to high temperature for a long period of time, as long tongues of granite run out into the dike-rock. In other cases merely remnants of inclusions over a foot in diameter are left, the greater part of the volume of the original block being filled with keratophyre mixed with the feldspars from the inclusion.

The origin of the inclusions of the igneous rocks must have been at some distance below the present exposure. No brecciation of the slate is observable at the surface, so it is thought that the inclusions of slate, which are often 2-foot cubes, and quartz, which are always small, also came from some depth, but not from such a distance as the igneous rocks. It is not known to the writer whether syenites, aplitic granites, and graphic granite outcrop farther inland or not. At Wells, 7 miles to the north, biotite granite is quarried.

The manner in which the inclusions of igneous rock, and possibly those of slate and quartz, were obtained is apparently by shattering, probably along the walls of the feeders of the sills. The resorption of the edges of the blocks must have been begun in depth where there was sufficient heat to assimilate a large part of an originally cubical block over 1 cubic foot in volume. However, as pointed out in other cases, if these blocks were shot up to their present position, the resorbed edges would be worn off; if they floated up, the resorbed edges would be partly preserved. Therefore, it is necessary to assume that the temperature of both the inclusions and the sill was nearly the same and that the corrosive action continued for some time after the blocks were at about their present levels, due to an additional supply of heat from below. This hypothesis is supported by the fact that where the margins of the sill are chilled, the inclusions in the marginal zones and also the more abundant inclusions in the center of the dike show fused contacts, but not extensive resorption. On the contrary, where there are no chilled margins, indicating that this part of the dike remained hot longer than the rest and then consolidated at one time, the inclusions all show resorption and assimilation and only skeletons are left of some of them. As the sill is of aschistic composition, such heating action is thought to be possible.

Rossland, British Columbia: During the C2 excursion of the International Geological Congress last summer, an inclusion-

bearing dike was observed by the writer at Rossland, British Columbia. The dike, which is known locally as the "White Dike," is 6 feet in width and consists of a mass of large bowlders imbedded in an augite kersantite matrix. Two types of bowlders were observed in the outcrop; one a white, fine-grained rock which was mistaken in the field for a quartzite, the other a bluish-grey rather coarse-grained rock with many small dark-brown patches. The texture of both is gneissic. A microscopic examination has shown that both types are anorthosite, the former consisting almost entirely of labradorite (Ab_{40},An_{60}), the latter of similar labradorite with small amounts of pyroxene, probably an orthorhombic variety with positive optical character. The pyroxene has in part altered to biotite and chlorite. Magnetite occurs in small amounts in both specimens. They both show the effects of some dynamic movement.

FIG. 2.—An exposure of the "White Dike" at Rossland, British Columbia, showing the abundance of inclusions. The sketch has been traced from a photograph. The scale is given by the width of the dike, which is 6 feet.

The inclusions vary in size, as shown in Fig. 2, the larger being 1 to 2 feet long. In shape they are partly angular, but in one of the surface exposures they are subangular or well rounded and do not have sharp edges, nor do the edges show any effect of corrosion. The inclusions weather out of the matrix, but slightly fused contacts are shown in the weathered material. The dike-rock consists of basic andesine or labradorite and augite phenocrysts in a matrix of labradorite, augite, biotite, and some magnetite.

The dike is in the extreme western portion of the Rossland district, about 5 miles north of the international boundary. It is shown on the Candian Geological Survey map of Rossland, at the western edge of the map, outcropping in a cut of the Great Northern Railway and at a flume 1,000 feet to the northwest. It cuts porphyritic monzonite in the first outcrop and augite porphyrite in the second. It has also been found in the 900-foot level of the Josie

mine, and it there presents the same appearance as on the surface and in the upper workings.[1] A similar dike has been found in the Columbia-Kootenay mine, but the inclusions are not as large as in the "White Dike."

The sedimentary rocks of the region consist, according to the map of the Boundary Creek mining district, of Paleozoic sediments, some of which are metamorphic, and Tertiary conglomerates and tuffs. The igneous rocks are of a number of types and represent several periods of intrusion. Gneisses of questionable age occur in the region, but no anorthosite has been reported.

Three explanations may be offered for the immediate origin of the inclusions:

1. The dike-magma may have come through a thick series of conglomerates of Paleozoic age and carried the pebbles and bowlders upward, dissolving their cement.

2. The dike-magma may have intruded Tertiary conglomerates, which have since been removed by erosion, the bowlders sinking in the molten dike-rock.

3. The dike-magma, when at some distance beneath the surface may have shattered off blocks of the rocks through which it passed, and carried them upward together with the blocks shattered in the formation of the fissure. The friction of the numerous inclusions against each other and against the walls of the dike would remove the angles and give the blocks rounded outlines.

These possibilities will be discussed in order.

1. If there were a thick series of conglomerates in the Paleozoic sediments, they should be exposed somewhere in the region, yet there are no conglomerates mapped in the surrounding 200 square miles (Can. Geol. Surv. Map No. 828). That the conglomerates would have to be of great thickness to furnish so many bowlders is shown by the known extent of the dike: 1,000 feet in length and 900 feet in depth.

2. If the dike had procured its inclusions from a Tertiary conglomerate, now largely eroded, there appears to be no good reason why a large majority of the inclusions should consist of a dynam-

[1] This information was kindly furnished by Dr. Charles W. Drysdale, of the Canadian Geological Survey.

ically metamorphosed rock which is not exposed at the surface. In the Boundary district there occur Tertiary tuffs and conglomerates overlain by basalts and other lavas, the bowlders as well as the matrix of these tuffs and conglomerates being largely of igneous origin. The conglomerates were apparently only locally developed, their formation being preceded and succeeded by volcanic activity.[1] The relative age of the dikes and the Tertiary sediments is not known.

3. The third theory involves shattering along the walls of the dike, the fragments being rounded during their ascent in the dike-rock. The explanation as to why the inclusions (so far as the writer is able to judge from the specimens collected) consist largely of anorthosite must lie in an unusual amount of shattering accompanying the formation of the dike-fissure in that very compact rock, while little shattering occurred in the younger intrusives which may still have been at a high temperature. It is certain that the presence of several million inclusions under the conditions described calls for extraordinary conditions.

The material which has been removed from the inclusions appears in part in the hand specimen of the kersantite as white xenocrysts of varying size. In the field these xenocrysts are not noticed, on account of the weathered condition of the rock. It is also probable that many of the feldspar phenocrysts—and perhaps even some of the pyroxene phenocrysts—of the kersantite are really xenocrysts of the anorthosite.

Little Belt Mountains, Montana: In the Little Belt Mountains Pirrson has described some minette dikes which have brought up masses of a plutonic rock from some depth below the surface.[2] One of the inclusions is a mica syenite, 2 to 3 feet in diameter. The minette does not show the least amount of endomorphic modification, but retains its normal minerals and structure to the contact. Pirrson writes: "From this we may infer that the mass was taken up while the magma was extremely hot, and that it had acquired very nearly the temperature of the fluid mass before the latter

[1] R. W. Brock, "Preliminary Report on the Rossland District," *Can. Geol. Surv.* (1906).

[2] *U.S. Geol. Surv., 20th Ann. Rept.*, Part 3, p. 536.

began crystallizing." The syenite has been somewhat altered by mineralizing vapors from the magma.

The sapphire-bearing Yogo dike also contains inclusions.[1] This mica-trap dike cuts Madison limestone. It is from 3 to 6 feet wide and is vertical. The dike walls are rough, but not especially irregular, and have been slightly indurated by the intrusion. In some places the upward termination is seen, as shown in Fig. 3. The fragments are angular and consist of limestone and shale from the Madison and underlying terranes. In the main excavations a similar breccia is shown at the surface, but the size and number of the fragments decrease with depth.

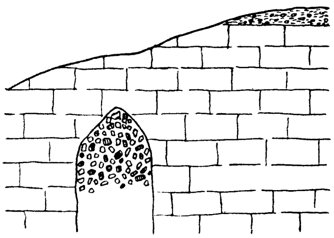

FIG. 3.—Section of upper limit of sapphire-bearing dike, wall of Yogo Canyon, Montana. The inclusions are limestone and shale fragments from the fissure walls, which have floated up to the top of the dike. (After Weed.)

The fragmental material has evidently been shattered from the fissure walls and floated upward as the molten rock rose in the fissure. The Yogo dike is the only case presented in this paper where the inclusions are proven to have floated up to the top of the dike. From the diminution in the number of inclusions with depth, it is evident that if the dike were exposed only at a lower level, few if any inclusions would be shown. On the other hand, inclusions are rarely present at the upward termination of dikes, or, if present, they have not been mentioned in the descriptions.[2]

Syracuse, New York: A few inclusion-bearing peridotite dikes at Syracuse, New York, have been described by several writers. The country rock is of Salina (Silurian) age. The inclusions are largely of Paleozoic rocks, but some are of pre-Cambrian gneisses. The latter are usually more rounded than the former, the result of the attrition involved in their upward journey.[3] In one dike

[1] W. H. Weed, *U.S. Geol. Surv., 20th Ann. Rept.*, Part 3, p. 455.

[2] Suess in *Das Antlitz der Erde*, Vol. III, Part 2, p. 658, describes several dikes the tops of which are exposed, but the above is the only one in which inclusions are mentioned.

[3] C. H. Smyth, Jr., *Amer. Jour. Sci.* (4), XIV (1902), 26.

which is 6 feet in width there are long, narrow inclusions of the country rock, one of which is 15 feet in length and about 1 foot wide with tapering ends. The thickness of the sedimentary rocks in the region is probably about 4,000 feet, and through this distance the pre-Cambrian inclusions have come.

Near Ithaca there are about 25 peridotite dikes, some of which contain a large number of shale and limestone inclusions from the country rock (of Upper Devonian age) and from the underlying Paleozoic sediments.[1] Similarly in the peridotite dikes of Elliott County, Kentucky, there are inclusions of acid (pre-Cambrian ?) rocks.[2]

Crazy Mountains, Montana: On the south side of Cottonwood Creek in the Crazy Mountains, Montana, are two elliptical stock-like masses of ouachitite breccia cutting flat-lying Fort Union, Eocene, shales.[3] The masses are 750 feet apart. The lower one is 200 feet long and 40 feet wide, the upper one 300 feet long and 200 feet wide. In each case the contacts are vertical and the igneous masses are jointed in both a horizontal and a vertical direction, the joints cutting both inclusions and cement. The fragments consist largely of fine-grained granitic gneiss, feldspathic quartzite, black slate, and granite. The outline of the fragments is subangular to angular. The interesting feature of these breccias is that the gneissic granite must be of pre-Cambrian age, as no such rock is exposed in the petrographical province. The thickness of the sedimentary series underlying the Crazy Mountains[4] is 24,000 feet, consisting of 4,500 feet of Algonkian, 3,900 feet of Paleozoic, 100 feet of Juratrias, and 15,500 feet of Cretaceous and Eocene strata. Therefore, the gneiss inclusions have apparently risen vertically for a distance of over 4 miles.

The origin of the inclusions was probably by thermal combined with mechanical shattering, as the magma has ascended in elliptical intrusions, replacing the country rock. The circulation in the

[1] *U.S. Geol. Surv., Geol. Atlas*, Folio No. 169, 1909.

[2] J. S. Diller, *U.S. Geol. Surv., Bull. 38*, 1887.

[3] The writer is indebted to Professor J. E. Wolff for the description of these breccias.

[4] W. H. Weed, *U.S. Geol. Surv., Geol. Atlas*, Little Belt Mountains Folio No. 56.

magma must have been very active to bring up blocks of gneiss from such a depth.

Beemersville, New Jersey: Near Beemersville and Libertyville, New Jersey, are several masses of breccia whose form suggests narrow volcanic necks or stocks. The occurrences have been described by Kemp[1] and by Wolff.[2]

The fragments are of various sizes from bowlders to fine grains and consist of gneiss, granite, limestone, and shale (the country rock), imbedded in an ouachitite. The shale inclusions show very sharp angular edges. The presence of inclusions of gneiss show that there has been vertical transportation of nearly a mile. Here again the elliptical-shaped intrusions have probably come up by replacing the rock through which they have passed, and the inclusions probably represent the stoped blocks.

There are also a number of lamprophyric dikes in the region which contain abundant inclusions of the rocks which they cut.

SUMMARY

Inclusions in dikes are rare and are due to special or to accidental causes. The majority of the inclusions have been shattered from the walls of the dike either in the formation of the fissure through which the dike came or in the injection of the dike-magma. The shattering is largely a mechanical operation, but thermal and mechanical action may be combined in many cases. In a few instances the inclusions are pebbles derived from a conglomerate.

The direction and amount of the movement of the inclusions in the several examples are shown in the table on p. 181.

In the cases where some inclusions rise and others sink in the same dike, as at LaTrappe near Montreal, the movement does not appear to depend as much upon the specific gravity of the magma relative to that of the inclusions as upon the mechanics of intrusion and the circulation in the dike-magma before its consolidation. Sandstone fragments have descended in this dike although their specific gravity when in the magma was probably

[1] "On Certain Porphyritic Bosses in Northern New Jersey," *Amer. Jour. Sci.* (3), XXXVIII (1889), 130–34.

[2] *U.S. Geol. Surv., Geol. Atlas*, Franklin Furnace Folio No. 161, p. 13.

less than that of the magma. In the other cases where the inclusions have sunk, the fragments are composed of various rocks including quartzite, sandstone, slate, limestone, gneiss, and diabase.

Examples	Movement of Inclusions		
	None	Up	Down
Cornwall	×	....	....
Mexico	×	....	....
Cape Ann	×	....	....
Montreal	×	3,000 ft.	2,000+ft.
Marblehead	....	....	1,000+ft.
Southern Sweden	....	....	×
Cripple Creek	....	....	×
Pequawket	....	....	×
Brazil	....	?	×
Shelburne Point	×	12,000+ft	....
Mancos	....	×	....
Aschaffenburg	....	×	....
Somerville	....	×	....
Rossland	....	×	....
Ogunquit	....	×	....
Little Belt Mountains	....	×	....
Syracuse	×	4,000 ft.	....
Beemersville	×	×	....
Crazy Mountains	×	24,000 ft.	....

Inclusions in dikes are in general rounded when they have come from some depth and angular when near the place of origin. This indicates that the rounding is largely due to friction which varies with: (1) the distance through which the inclusion has moved, (2) the number of the inclusions; (3) the width of the dike, (4) the temperature of the inclusion at the time of the shattering, (5) the rate of movement of the inclusion.

The initial temperature of the outside of an inclusion is the mean between that of the magma and that of the center of the inclusion. Hence, if there is a fused contact around an inclusion or if the latter shows resorption, a high temperature of the whole fragment is indicated. As most dikes are quickly chilled, it is seldom possible to heat cold inclusions to a temperature at which fusion can take place around their peripheries. In dikes several hundred feet wide, as those of southern Sweden, cold inclusions may be heated to such a high temperature that partial resorption results. In narrower dikes, partial resorption of fragments is possible only

where a special mechanism for the transfer of heat from depth exists for a relatively long period of time, as in a part of the Ogunquit dike.

The material worn from fragments during their rounding and the cement which is dissolved from conglomerates appear in the dike as xenocrysts. Thus, in the hand-specimen of the Rossland dike many small fragments of quartzite and gneiss one-quarter of an inch or less in length may be seen. In the Brevik (Sweden) dike Hedström reports grains of quartz and feldspar of microscopic size derived from the matrix of the conglomerate. In the Somerville dikes numerous xenocrysts of quartz and andesine feldspar, which have come in part from the inclusions, are found in the groundmass. The Shelburne Point dike described by Hitchcock contains many small fragments of the inclusion-rocks.

The question of the fragmentation of rocks from the differential expansion of the constituent minerals and the importance of the inversion point of quartz are of bearing in quartzose inclusions only in the cases where the inclusions have been heated to about 575° C. The criteria of high temperature of the inclusions, at the time of the chilling of the dike, are fused contacts or evidences of corrosion. In part of the Ogunquit dike there is evidence of high temperature and partial assimilation of the inclusions, most of which contain only a small amount of quartz. This corrosion apparently proceeds by the fragmentation of the minerals, as xenocrysts are exceedingly abundant in the dike-rock. In the Somerville dikes the inclusions of feldspar and vein quartz show marked corrosion, yet there is no sign of fragmentation at their peripheries. In the Aschaffenburg dikes there has been a selective formation of xenocrysts of certain minerals as if the rocks had been disrupted by the unequal expansion of the different minerals.

In conclusion it may be stated that some knowledge concerning the mechanism of dike-injection may be gained by the consideration of the movements of the inclusions. Further observations are needed concerning the possibility of circulation which will cause inclusions of lesser specific gravity than the dike-magma to descend in dikes.